Nonlocal Gravity(Digest_要約)

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In this thesis, we study the cosmological correspondence of nonlocal gravity, which is an infrared (IR) modification of Einstein's theory.

Despite of the great success of General Relativity (GR), it is widely known that GR suffers from the Cosmological Constant Problem (CCP), which is one of the most severe problems in fundamental physics. A related cosmological mystery is the dark energy problem, namely, what drives the current accelerated expansion of the universe? Aiming at the resolution of these two problems, a nonlocal modification theory of gravity that may originate from the loop corrections to GR was proposed. In this theory, on cosmological scales, it is hoped that the observed accelerated expansion of the current universe can be explained by the nonlocal modification term while leaving the large bare vacuum energy predicted by quantum field theory unchanged. Moreover, with an appropriate reconstruction procedure, one can construct a model, though with rather unnatural tuning, in which the evolution of the universe is indistinguishable from that predicted by the ΛCDM model.

Chapter 1 is devoted to the introduction of these issues and topics. In Chapter 2, to motivate the research performed in this thesis, we reviewed the Cosmological Constant Problem in some detail.

Then in Chapter 3, we briefly reviewed the fundamental elements in nonlocal gravity. Part of the motivation of the theory is solving CCP in cosmology. We formulated the action and the equations of motion. The original form of equations of motion contains double integration. The difficulty of the double integration can be eased in two ways: choosing appropriate boundaries for integration or localize the action. We present these two ways, respectively. It was found that in the biscalar-tensor presentation (i.e. localized action), there is a ghost-like mode resulting from aa extra degree of freedom of in the choice of the boundary condition. This is the only non-equivalence between the two forms. Because of the simplicity of biscalar-tensor presentation, we mainly worked in this form.

In Chapter 4, towards a realization of the proposal of solving CCP in nonlocal gravity, we introduced a bare cosmological constant into the nonlocal action and give two explicit examples for this proposal. In the first example, a flat spacetime solution was found in the absence of matter for a quadratic function $f(\psi) = f_0\psi + f_1\psi^2$. However, this solution might suffer from an unnatural tuning on parameter f_1 because of a would-be ghost instability, though it may not be physically relevant. In the second example, for a simple exponential function $f(\psi) = f_0 e^{\alpha\psi}$, we found two branches of vacuum power-law solutions: decelerated and accelerated expansion solutions. In these solutions, the effect of the bare cosmological constant term is effectively shielded without fine tuning of its value. The decelerated expanding solution was free from the would-be ghost problem provided that the parameter $\alpha > \alpha_{cr} \approx 0.17$. The accelerated branch suffered from the would-be ghost problem, though this problem might not be physically relevant.

Following this, we searched for general cosmological solutions with a simple class of models where the nonlocal function took the exponential form

$f(\psi) = f_0 e^{\alpha\psi}$. Firstly, we analyzed the de Sitter solutions. It was found that for vacuum case, a de Sitter solution exists only for $\alpha = 1/2$. When a perfect fluid is introduced, the parameter range for the existence of a de Sitter solution becomes $\alpha < 1/2$, and its value is related to the EoS parameter w_m. Moreover, the stability of the vacuum de Sitter solution was verified. Hence, the early and late accelerated expansion of the universe can be obtained in nonlocal gravity. As a description of the decelerated expansion epoch between these two stages, we furthermore explored power-law solutions with a perfect fluid. We obtained all the possible power-law solutions in Jordan frame. We also clarified the correspondence between Jordan frame and Einstein frame. Using this relation, a series of power-law solutions in the Einstein frame were found. These solutions will play an important role for analysis of the whole history of universe in nonlocal gravity.

In the modified gravity theories, the background evolution may not be sufficient to determine the model uniquely. Hence, in Chapter 5, we considered the linear cosmological perturbations in nonlocal gravity. After a brief review of the linear cosmological perturbation theory, we derived the perturbation equations in nonlocal gravity, in the form of its biscalar-tensor representation. As an application of these equations, we paied attention to the Newtonian limit and obtained the corresponding effective Newtonian constant and the post-Newtonian parameter. Using the experimental bound from the time-delay effect of the Cassini tracking for the sun, we obtained the corresponding constraint on the parameters in nonlocal gravity. It was found that for a wide range of model parameters, nonlocal gravity theories can satisfy the local constraints.

Finally, we argued that since the Hubble parameter of the de Sitter solution found for a particular theory of nonlocal gravity is a free parameter specified by the initial condition, not by the parameter of the theory, there is a hope that nonlocal gravity can describe both a proper inflationary scenario in the early universe, subsequent decelerated expanding phase of the universe, and the current accelerated expanding phase, irrespective of the value of the bare cosmological constant in the Lagrangian, thus giving a solution to the cosmological constant problem. We then conclude by stating a few important future issues including the search for a theory that properly reproduce both the early inflationary phase and the current accelerated phase simultaneously without fine-tuning of the model parameters.

The contents of the thesis are as follows: